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INVESTIGATION OF DIRECT AND ALTERNATING CURRENT GLOW ANEMOMETERS

by

A. J. A. Morgan and T. Vrebalovich

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SUMMARY

The glow anemometer is particularly suited for the measurement of turbulence in applications for which the hot-wire is unsuitable. This is especially the case in supersonic air streams where the strength and frequency response of the hot-wire are limiting factors.

The experimental work, so far, has been directed towards the perfection of a workable instrument with the characteristics desired for the above-mentioned applications. A resume of this work is given in the present report and divides itself naturally into three sections:

1. The Direct Current Glow
2. The Intermittent Glow
3. The Alternating Glow
   (a) Low Frequency
   (b) High Frequency

Because of the confusion in terminology which exists in the present-day literature on the anemometric applications of glow discharges, it was thought expedient to define our terms in the introduction.

1.00 INTRODUCTION

A knowledge of the turbulence level in wind tunnels was found necessary to evaluate properly force measurements on bodies in subsonic flow. Similar information is almost certainly required in supersonic flow. For example, the effect of free stream turbulence on boundary layer transition and skin friction in supersonic flow is, so far, not known quantitatively.

Hence, judging from present experience with subsonic flows, it appears to be essential to know the free stream turbulence in supersonic wind tunnels in which force measurements are being performed. Such a knowledge of the external flow field would make a quantitative evaluation of these experiments possible. Besides the above described influences of turbulence a knowledge of the turbulence problem itself, for supersonic flows, is a subject towards which increasing interest is being directed.

At the present time the hot-wire anemometer is being used to measure turbulent velocity fluctuations up to 20 KC. This frequency range is ample for low subsonic speeds.* As the velocity increases the diameter of the hot-wire must be increased (for greater strength), but for high frequency response its diameter must be decreased. These two opposing requirements can not be easily reconciled at high subsonic and supersonic velocities when the turbulence spectrum is expected to extend to frequencies of the order of 50 KC.

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*The spectral range of isotropic turbulence at 10 m/sec. extends from zero to approximately 5000 cycles per second (Ref. 1).

It is evident that an extension of hot-wire measurements to high subsonic and supersonic velocities is difficult, and the question clearly arises as to whether a different and more suitable technique for turbulence measurements at high speeds may be developed. Experiments by Fucks and Kettel (Ref. 2), Mettler (Ref. 3) and the present authors indicate that the glow anemometer shows considerable promise for measurements of this type.

A glow anemometer is essentially a device which uses the influence of a moving air-stream upon an electrical discharge between two electrodes as a means of measuring the air velocity. One evident difficulty with most anemometers using electrical discharges is the fact that the actual mechanism of interaction between the air stream and the discharge is extremely complex and cannot, so far, be expressed in a simple analytical form. Therefore, the use of the instrument always relies on a calibration procedure. To a certain extent this is equally true for hot-wire measurements where the mechanism of heat removal is too complex for complete analytical formulation, and calibration is also required.

1.10 Definitions

A great deal of confusion exists in the literature with respect to the terminology used in the description of electrical discharges which have been investigated for their anemometric applications. Instances of this will be noticed on comparison of the reports by Fucks and Kettel (Ref. 2), Mettler (Ref. 3), Lindvall (Ref. 4) and Werner (Ref. 5). Because of this confusion we have found it advisable to define our terminology precisely.

For a given electrode spacing and configuration a plot of the voltage and current across two electrodes has the general character shown in Fig. 1.

The different regions indicated on the curve are not sharply divided and in fact blend one into another in a gradual manner. They are so distinguished because, in general, they correspond to different physical mechanisms in the production of the electrical discharge. The definitions commonly accepted in electrical engineering practice are:

1.11 Dark Current or Townsend Discharge (Ref. 6)

This region corresponds to voltages of from 6 to 12 KV and currents from 10^{-12} to 10^{-9} amperes. In this case a continual source of external excitation, such as cosmic rays or x-rays, is required to provide a constant flow of current. A strong electric field is required to transport the ionized molecules of the gas within the electrode gap to the cathode.

1.12 Corona Discharge

The corona discharge, under atmospheric pressure, is a self-sustaining, high voltage (8 to 15 KV) and low current (10^{-7} to 10^{-6} amp) electrical discharge. In a negative point corona (i.e., the negative electrode is a point) light is emitted near the negative point. For similar configurations and external parameters (pressure, temperature, electrode material, etc.) the corona discharge operates at both higher voltage and current than the "dark current" or Townsend discharge, as is illustrated in Fig. 1.

1.13 Glow Discharge

The mechanism of a glow discharge is much more complex than that of a dark current discharge. As opposed to the dark current discharge, a glow discharge sustains itself without any external excitation; furthermore, the field distortion caused by the space charge is an inherent part of the sustained operation of the glow. The essential characteristic of the glow discharge is that the voltage remains very nearly constant with changing current (Ref. 6). The voltage and current ranges are from 300 to 700 volts and 2 to 25 mA. These depend on the electrode spacing, configuration, the gas and the gas pressure.

1.14 Arc Discharge

The electric arc is a self-sustained discharge having a low voltage drop and capable of sustaining large currents. The electrodes are usually at the boiling temperature of the materials used. The mechanism by which the arc is sustained is also quite different from that of the glow, the difference being the role which thermionic emission plays in the production of ions and electrons.

The above definitions are by no means exhaustive in character but are sufficient for our present purposes. Detailed discussions of the different discharge regions defined above are given by Cobine (Ref. 6) and Loeb (Ref. 7).

We shall later have occasion to use further terminology which we here define.

By sputtering we shall refer to the continual disintegration of the cathode surface caused by the severe bombardment by positive ions to which the cathode is subjected in a glow discharge.

It sometimes occurs that the glow, after it has been established, will suddenly be extinguished for no apparent reason and it often reignites itself. This usually occurs when the glow is operating in an air-stream. We shall refer to this phenomenon as an <u>instability</u> of the glow.

In the succeeding sections we shall restrict ourselves to a discussion of different types of glow discharges (in strict accordance with our definitions) which have been treated in the course of the investigation reported herein.

1.20 <u>Reasons for Selecting Glow Discharge</u>

The glow discharge has the advantage of a conveniently and easily managed voltage range. The voltage fluctuations caused by a fluctuating air velocity are sufficient to eliminate the need for any additional amplification. Of major importance (in so far as the aerodynamic applications of the glow are concerned) is the fact that the low operating voltage allows the probe, into which the electrodes are built, to be small yet aerodynamically sound.

A definite disadvantage of the direct current glow discharge anemometer is electrode sputtering. The presence of electrode sputtering seriously complicates the calibration and operating techniques. These difficulties will be discussed in detail in a later section.

In the dark current and corona discharge there is no sputtering, but the operating voltages are so high that insulation difficulties require that a large probe be built to hold the electrodes. This, of course, is unsuitable for aerodynamic measurements, especially in the high speed range. The arc discharge has such a high noise level and high electrode erosion rate that it is unsuitable for use in turbulence measurements.

For the above reasons it was felt that the advantages of the glow discharge far outweighed the sputtering disadvantage for its use as a turbulence measuring instrument. In the following sections we shall report on the attempts made to eliminate this disadvantage.

1.30 Review of Literature

A comprehensive review of the literature on the anemometric application of glow discharges has been given by Mettler (Ref. 3). It will here suffice to say that Phillips (Ref. 8) in 1923 first used the glow as the sensitive element of a microphone. Lindvall (Ref. 4) in 1934 was the first to suggest its use as a turbulence measuring instrument. In 1941 a group of investigators in Germany became interested in Lindvall's work and, under the sponsorship of Deutsche Versuchsanstalt Fuer Luftfahrt, began studying the use of gas discharges to measure turbulence in air. Their work is currently available in a series of microfilms (Ref. 2) and in an N.A.C.A. publication (Ref. 9). As pointed out by Mettler, many of the conclusions reached by the German group were erroneous in view of the present experimental data. Many of the data obtained by Mettler (in collaboration with one of the present authors -- Morgan) for direct current glows are available in the form of a Doctoral Thesis (Ref. 3). Some of these data will be reproduced here for completeness and in fact form the basis for the current research program.

Recently Werner (Ref. 5) published a report on the anemometric applications of a corona (which he calls a glow) discharge. Although he does not show the velocity dependence of the corona discharge directly, it can be obtained by cross plotting the data of Fig. 12 in

Ref. 5. The velocity characteristics obtained in this manner are similar to those of the glow anemometer. Werner's present instrument configuration (Fig. 10, Ref. 5) makes it unsuitable for turbulence measurements. Furthermore, no data are given on the time stability of the corona discharge, which is a measure of the constancy of the calibration, and as a consequence one cannot be certain as to the length of time between calibrations required for satisfactory operation.

The mechanisms of the corona and dark current discharges are not markedly different. Mettler has shown that the changes in current with velocity in a dark current anemometer can be predicted by assuming that the transverse air stream causes a loss of positive ions. The preponderance of evidence, both experimental and theoretical, indicates that this belief is correct. Werner, on the other hand, states that this is not the case. However, Werner's arguments do not appear entirely convincing.

Fucks (Ref. 10) recently investigated the "dark current" and corona discharges with reference to their anemometric applications. From the "turbulence measurement" point of view Fucks uses suitable electrode configurations but does not give any circuit diagrams or pictures of his set-up from which it would be possible to evaluate the usefulness of his instrument as a turbulence measuring device.

In so far as alternating current glows are concerned, a review of the literature shows that the only existing work on this subject appears to be contained in a report by Fucks and Schumacher (Ref. 11). According to this report the alternating glow is a definite means of avoiding sputtering. This idea forms the basis of the research program which is reported herein, and the reasons for this conclusion are fully discussed in Section 4.00. A frequency of 500 cy/sec. was used in the experiments by Fucks and Schumacher, and at the low speeds investigated this frequency lies within the most important part of the turbulence spectrum. Therefore, the alternating glow used by Fucks is unsuitable for turbulence measurements. Any instrument of this type must operate at a frequency which falls outside the interesting part of the turbulence spectrum; i.e., the frequency has to be either very high or very low. The circuits used by Fucks and Schumacher do not allow for the close control of the current and voltage which is required for precise experimental work of this nature.

2.00 EXPERIMENTAL TECHNIQUES

2.01 Electrode Shape

In order to minimize the number of variables affecting the glow, the electrode shape was held constant. Hemispherical and flat-tipped electrodes were used in these experiments. The flat electrodes were polished by using a holding jig (Fig. 2) which held the electrodes in a vertical position. The platinum tip protruded slightly from the flat surface of the jig. This jig was rubbed across a fine oilstone and then across polishing compounds. This treatment assured uniformity in the surface conditions of the flat electrodes.

The hemispherically tipped electrodes were made by holding the electrode in a special jig (Fig. 3), and cold forging a hemisphere on the tip by striking the die when the tip was in the proper position. The points were then polished on a lathe. By the techniques employed, geometrically similar flat and hemispherically tipped electrodes were easily produced.

2.02 Electrode Surface Condition

From experiments performed by Mettler and others involving electrical discharges in gases (Ref. 3) it seemed advisable to make the electrodes as smooth as possible. Irregularities in the electrode surface induce local effects in the burning of the glow which may affect the stability of the glow. Bumps or pits, undetectable except under a microscope, in the surface of the electrode cause discontinuities in the electrical field gradients which, in the case of a point, cause a concentration of electron flow in this region. Such an effect will raise the local temperature, melt the metal, and cause material transport from the point -- this is one of the factors which cause sputtering.

In order to reduce the above mentioned effects, several polishing techniques were tried. Flat points were polished on oilstone, on glass with a levigated aluminum compound, on glass with jeweler's rouge, and on glass covered with hard silk with levigated aluminum. Examination of the points under a microscope indicated that polishing on silk-covered glass with levigated aluminum gave the best surface.

After cold forging, the hemispherical points were very smooth, and, in order to insure the best possible surface, they were polished in a jeweler's lathe by holding levigated aluminum impregnated silk against the rotating points. The surface obtained in this way was as good as that obtained on the flat points.

In order to make sure that no impurities were left on the electrode surfaces, they were cleaned with carbon tetrachloride and dilute nitric acid.

2.03 Probes

Two probes (Fig. 4) were used in the direct current glow experiments. One was used for high velocity and the other for low velocity. The low velocity probe had adjustable electrodes and was used in conjunction with a gap-spacing jig. The distance between electrodes (gap) can be set to one ten-thousandth of an inch (0.0001") by use of a microscope comparator. The gap-spacing jig, low velocity probe and comparator are shown in Fig. 5. The structural rigidity of the low velocity probe was sufficient to hold the gap constant while the probe was in an air stream.

The high velocity probe (Fig. 4a) was designed for minimum flow interference. The gap was not adjustable and had to be pre-set. This gap changed when the probe was placed in the air stream and had to be computed from photographs.

2.04 Electrode Material

Mettler carried out experiments to determine what electrode material would give minimum sputtering and maximum stability to a glow discharge under atmospheric pressure. The materials tested were aluminum, iron, copper, tungsten, platinum, duraluminum, and elkonite, and of these it was found that platinum was the only material which gave a low enough noise level and sufficient stability to be used for a glow discharge under atmospheric pressure. It was also found that tungsten and tantalum could be used satisfactorily for the anode when platinum was used for the cathode. Fucks and Schumacher (Ref. 11) successfully used palladium and iridium electrodes.

In the present research platinum electrodes have been used exclusively. The purity of the platinum was 99.8%.

2.05 Tunnel

For the low velocity calibration runs an eight inch open jet wind tunnel was used. The tunnel had a velocity range of five to thirty meters per second. The probe was mounted on a traversing stand by means of which the probe could move in the direction of the air stream. A pitot tube and a Zahm type micromanometer, capable of measuring pressure differences to 0.01 millimeters of alcohol, were used to measure the free stream air velocity. The pitot tube was mounted on the traversing stand near the glow probe. Fig. 6 shows the probe, pitot tube and tunnel throat. Mettler used the GALCIT 4 x 10 inch transonic tunnel for tests in the supersonic speed range.

3.00 THE DIRECT CURRENT GLOW

In this section we shall present a set of experiments performed by Mettler and some recent experiments carried out by the authors on the direct current glow.

3.01 Equipment

Mettler used an existing half-wave rectifier power supply. This equipment was only useful in so far as it indicated the practicability of using a glow for anemometric purposes. With this equipment a noise level of 0.004 volts was obtained across a glow operating in still air.

An especially designed power supply was then built. The circuit used is shown in Fig. 7. It will be observed that the circuit is very simple, consisting only of a power supply, current regulator and measuring circuits, in addition to the glow discharge itself. The physical arrangement of the circuit is shown in Fig. 8. The power supply and current regulator unit is shown in Fig. 9. With this equipment a noise level of 0.0018 volts was measured across a glow operating in still air and, in this respect, a twofold improvement over Mettler's equipment was obtained.

3.10 Experimental Results

3.11 Zero Velocity Data

The zero velocity data are contained in a previously mentioned report (Ref. 3). It will suffice here to remark that the effect of pressure (7.5 to 30 psi) on the glow was small and could not account for the large voltage changes across the glow when it was placed in an air stream. Also, ambient temperature and time of operation were shown to have a negligible effect on the direct current voltage across the glow after an initial "settling down" period of two (2) to ten (10) minutes.

3.12 Subsonic Velocity Data

The glow was operated in the eight inch open-jet tunnel described previously (Section 2.00). The object of the tests was to determine whether or not the glow discharge could be used to obtain quantitative measurements of turbulence at low air speeds. Different electrode configurations were tried, and these are schematically indicated in the figures (Figs. 10, 11, 13 and 14). Some of the purely mechanical difficulties encountered in the probe and electrode manufacture are discussed in Section 2.00. Observation of the glow (with cathode and anode diameters of 0.030 inches) under a microscope while the air velocity was being varied revealed that, whereas the cathode glow appeared to move uniformly downstream as the velocity was increased, the anode glow appeared to shift suddenly from point to point on the anode surface. By decreasing the size of the anode to 0.010 inches in diameter, the movement of the anode spot was further restricted and the scatter in the data was somewhat reduced. For best operation the current was adjusted to allow the cathode glow to cover the cathode area at zero velocity. As the velocity was increased, stable operation was possible until about one-quarter of the cathode glow had moved around the edge of the electrode. Further velocity increases caused instability.

3.13 Calibration Curves

A typical set of calibration curves is shown in Fig. 10; each point was obtained under equilibrium conditions. These characteristics were intended to be used in the following way: The inverse of the slope of the curve of voltage (V) versus velocity (U), at any mean velocity, is $\Delta U/\Delta V$. Measured alternating voltages (ΔV) caused by turbulence can be converted to alternating velocities (ΔU) by multiplying this ratio by ΔV. This is legitimate if such alternating voltages are so small that the curve is essentially linear in the range traversed. Such a calibration procedure assumes that at the frequencies considered, the curve taken under equilibrium conditions will also represent the dynamic response. Qualitative arguments, based on electron mobility data, indicate that the dynamic response of the glow is the same as its "equilibrium" response (Ref. 3). This property of the glow has not, as yet, been experimentally investigated. It will be observed that, by properly selecting the spacing, several sensitivities are made available in any particular velocity range. Those portions of the curves which indicate that the glow is velocity sensitive and which are essentially linear would presumably be used whenever possible, e.g., Curve 1, Fig. 10, from 13 to 16 m/sec. The curve given in Fig. 10 for a spacing of 0.0067 inches shows a definite deviation from the general trend of the other curves in the vicinity of 14 meters per second. Such behavior was not characteristic of any particular spacing or of any particular velocity range. Not all sets of calibration curves showed such an anomaly. However, since such behavior could not be predicted, and was never entirely eliminated, a set of calibration curves illustrating such behavior is presented in preference to a smooth set.

Curves taken at other values of current are similar in their dependence upon spacing. However, at a given spacing, decreased current causes the voltage to increase more rapidly with velocity and raises the level of the entire curve.

It required about an hour to take the data for one velocity characteristic such as those shown in Fig. 10, since at each point the glow was allowed to operate for several minutes to insure the attainment of equilibrium conditions. If the voltage were again recorded as the velocity was slowly reduced, it was found that the curve did not exactly retrace itself; the amount by which the curves failed to retrace themselves increased if the current were increased. This pseudo-hystersis effect was attributed to sputtering of the electrodes. This effect is illustrated by Fig. 11, where the upper curve of Fig. 10 is re-plotted, and the points taken as the velocity was slowly decreased are included. It will be observed that the direct current voltage level of the curve is raised about one part in one hundred by sputtering; the slope of the curve, from 12 to 16 m/sec., is not changed a great amount.

It was felt necessary in the present research to repeat some of Mettler's work with the equipment shown in Fig. 8. The initial objective was to obtain a complete set of calibration curves which could be used for selecting the electrode spacing and current suitable for obtaining adequate velocity sensitivities at a given velocity. This objective has not been attained at the time of writing. It was found that the sputtering caused enough scattering of the data so that the calibration curves were not reproducible. The effect of sputtering on the electrode surfaces is shown in Fig. 12. The circular depression in the cathode surface (Fig. 12a) indicates that the glow "settled down" in this region. Since the velocity is from left to right, the region of the circular depression is to the right of the center of the cathode. For the same reason the concentration of small pits on the anode surface is to the right of the center of the anode. It was then decided to investigate different polishing techniques (Section 2.00) and decrease the time necessary to obtain data for a calibration curve.

The effect of instabilities on the voltage-velocity curves is shown by Curve 1, Fig. 13. From this curve it is evident that instabilities raise the voltage level of the curve. Curve 2 was obtained by subtracting the voltage rises, referred to the data point at 8.7 m/sec. (Curve 1), due to instabilities from the original data (Curve 1). This curve is smooth and compares, within the experimental scatter, with data for which no instabilities were observed (Curve 3). The spread in the curves is probably due to slight variations in the electrode gap spacing and polish and to the non-parallelism of the electrode surfaces. The curves of Figs. 10 and 13 exhibit the same type of velocity dependence.

The effect of electrode shape on the voltage-velocity characteristics of the glow (at a given spacing and current) is shown in Fig. 14. These curves are plots of $V - V_o$ versus U, where V is the voltage across the glow at the air stream velocity U and V_o is the voltage across the glow at $U = 5$ m/sec. The curves were plotted in this way for ease of comparison. It will be noted that the data for the hemispherically tipped electrodes indicate a high velocity sensitivity at air stream velocities of 10 to 13 m/sec. The curve for the asymmetric flat electrode shows that a similar velocity sensitivity is obtained at air stream velocities of 14 to 17 m/sec. A comparison of the characteristics for the asymmetric flat electrodes of Fig. 14 and Fig. 10 (obtained by Mettler) on the basis a $V - V_o$ versus U plot, at the same current and spacing, shows that the two curves check each other very closely. An extrapolation of the curve for the symmetric flat tipped electrodes indicates that the same velocity sensitivity can be obtained in a higher velocity range ($>$ 17 m/sec.). The effect of electrode shape on the velocity characteristics is, to a large extent, due to the way in which the anode spot is restricted in its movement with changing air velocity; a further discussion of this is given in Ref. 3. A variation of the electrode shape then provides another means of controlling the velocity sensitivity of the glow.

3.20 Supersonic Velocity Data

The problem of making measurements in a supersonic air stream with a probe-type instrument is complicated by the formation of shock waves ahead of the probe. It is impossible to make direct measurements of free stream conditions by inserting a probe of any kind into a supersonic flow. One can only measure the conditions behind the shock wave formed ahead of the probe. If the strength of the shock wave is known and if the manner in which a shock wave alters the quantity being measured is known, then the free stream conditions can be calculated from the measured data. Since the available information on free stream "turbulence" in a supersonic air stream, and its interaction with a shock wave, is meager at best, its measurement by means of any probe-type instrument will be quite difficult.

The glow discharge anemometer was tested at supersonic velocities in the GALCIT 4 x 10 inch transonic tunnel (Fig. 15). It was found that the glow was stable and could be operated over a wide range of currents. Fig. 16 shows a Schlieren photograph taken while the glow was in operation in a supersonic air stream. The photograph shown as Fig. 17 was taken at the same Mach number with the glow absent. By superimposing the negatives of these photographs, it was observed that the glow discharge did not affect the shock wave system. These figures show that the shock wave with the probe used is detached and that, just ahead of the glow, it is normal to the flow direction. The action of the air stream in forcing the glow to the downstream side of the electrodes is also demonstrated. Careful visual observation of the glow while it was in the air flow revealed a luminous region trailing out of the downstream side of the discharge. This was interpreted as being visual evidence of the loss of positive ions out of the discharge.

A typical set of current-voltage data, taken at a Mach number of about 1.2, is given as Fig. 18. The glow was stable at this Mach number at a current as low as six milliamperes and was observed to become more stable as the free stream Mach number was increased. This behavior is different from that observed at high subsonic velocities, where currents of the order of 20 milliamperes were required for stable operation and increasing the velocity made it more difficult to maintain a stable glow. There are two reasons for this difference. At the Mach number and stagnation pressure at which these data were taken, the pressure behind the normal shock wave just ahead of the glow is only about 0.65 times the atmospheric pressure; this reduction of pressure is favorable to the stability of the glow. Secondly, since the product of the velocity ahead of and behind a normal shock wave is a constant, the velocity in which the glow discharge finds itself decreases as the free stream Mach number is increased.

A typical curve of the direct current voltage across the glow discharge as a function of the free stream Mach number, at constant current, is given in Fig. 19. In view of the discussion in the preceding paragraph, it is not surprising to see that the voltage decreases as the Mach number is increased.

A qualitative indication of the response of the glow discharge to the velocity fluctuations in a supersonic air stream was obtained by observing the oscilloscope as the probe was moved into the boundary layer, which was visible on the Schlieren viewing screen. Outside of the boundary layer the alternating voltage signal observed on the oscilloscope was of the same general nature as that observed at subsonic velocities but was at a much higher frequency. As the probe was moved into the boundary layer, this signal was increased about tenfold. The alternating signal was also observed as the probe was traversed through the wake of a 0.014 inch wire which was stretched across the middle of the test section. At a distance of eight centimeters behind the wire, a peak was observed in both the alternating signal and the direct current voltage as the probe passed through the top and bottom of the wake; between these peaks (i.e., directly behind the wire) the voltages dropped to a value about equal to that observed several centimeters above and below the wire. At a distance of 35 centimeters behind the wire, a single smaller voltage peak extending across the entire wake was observed. It thus appears that the glow discharge responds, at least in a qualitative way, to velocity fluctuations in a supersonic air stream.

4.00 LOW FREQUENCY ALTERNATING GLOW

In order to overcome the antisymmetry in the burning of the direct current glow (Section 3.00), an alternating current instrument was constructed. It was felt that the alternating glow would eliminate the uneven burning of the electrodes and reduce sputtering and its effects (Refs. 3 and 11).

In order to make use of the current regulating feature of the direct current glow instrument, an electronic switching circuit (Fig. 20) was constructed which could be used in conjunction with the direct current regulator.

While the elements of the switching circuit were being adjusted, an intermittent glow was obtained by using two tubes (Fig. 20 tubes A and C) of the switching circuit. These tubes switched the glow on and off at frequencies from 7 to 50,000 cycles per second. When turbulence was introduced into the air stream, a cathode ray oscilloscope connected across the glow showed turbulence superimposed on the voltage wave shape of the 50 K.C. intermittent glow. The effect of turbulence on the low frequency intermittent glow was similar to that on the low frequency alternating glow obtained by using the switching circuit of Fig. 20. This will be discussed later in this section.

The output of the switching circuit was a square wave voltage for a constant resistance load. An igniting glow is not a constant impedance (Fig. 1); consequently the output voltage of the glow was a square wave with a high voltage peak at the beginning of each wave, as shown in Fig. 21. This high voltage peak is due to the high breakdown voltage needed to strike a glow. Unless the wave front of the square wave is extremely sharp, the air in the gap will deionize, and the glow will then have to be reignited each time there is a voltage reversal, as was the case for the switching circuit used. The mechanism of this breakdown phenomenon has been discussed in the direct current glow section.

Another reason for wanting a steep front square wave is that, because of the high voltage present at the beginning of each wave, it is possible for some current to bypass the glow by being conducted through two of the switching tubes (Fig. 20 tubes A and C, or B and D) which are in series. If this current becomes appreciable, it is not possible to get a high enough voltage to reignite the glow, because of the current regulating characteristics of the direct current supply.

By using the switching circuit (Fig. 20) with the direct current regulator, a stable alternating current glow, between 7 and 2,000 cycles per second, was produced. Hemispherically tipped electrodes were used, and these were in extremely good condition after being used in the alternating current glow for more than an hour. Under a 30 power microscope the surface of the electrodes looked very finely etched. Fucks and Schumacher got a similar result with their alternating current glow (Ref. 12). Under a microscope the glow looked as if it had spherical shaped calottes near each electrode.

A cathode ray oscilloscope was connected across the glow in order to observe the wave shape of the glow voltage and the effect of turbulence on this wave shape. To produce turbulence a small obstruction was moved in front of the glow while it was in the air stream. For switching frequencies between 7 and 2,000 cycles the wave shapes with no turbulence (Fig. 21a) were similar, except for some distortion at the extremely low frequencies and at the high frequencies due to the frequency response of some of the components of the switching circuit. When turbulence was introduced, the square wave had small fluctuations superimposed on the wave (Fig. 21b) -- the high voltage peaks were retained. The high frequency square wave also tended to be modulated by the turbulence, since some of the turbulence frequencies were less than the frequency of the alternating glow. Especially noticeable at the high switching frequencies was the change in magnitude of the starting pulse, due to the low frequency turbulence. At these switching frequencies the starting pulse as well as the wave was modulated by the turbulence.

In order to use the alternating current glow effectively, some method which will eliminate the starting pulse on each square wave must be found to read voltages and currents across the glow. Faster switching might eliminate this effect. The pulse could of course be electronically blanked out in some complex manner. It is also desirable to use a frequency outside the range of turbulence frequencies. For the above reasons, it is evident that this instrument could only be used at the low frequencies, since the high frequencies at which it can be operated lie within the turbulence frequency range.

It is felt that with further development of the switching and recording circuits the low frequency alternating glow may be used to measure turbulence.

5.00 HIGH FREQUENCY ALTERNATING GLOW

Once it was shown that a low frequency alternating glow could be maintained, it was decided to construct equipment for producing a high frequency (100 KC) glow. Some of the disadvantages inherent in the low frequency glow (Section 4.00) would then be eliminated.

As a first attempt a 100 KC glow was produced by using a push-pull negative resistance oscillator circuit (Fig. 22). Although it was not possible to maintain constant voltage, current or frequency with this circuit, several important properties of the 100 KC glow were qualitatively established. These will be discussed below.

It was possible to maintain the 100 KC glow at electrode spacings varying from 0.002 to 0.012 inches. This implies that it is possible to adjust the electrode spacing to obtain desired velocity-sensitivities of the glow at a given velocity.

Visual and microscopic examination of the electrodes, initially highly polished, showed that their polish had not been destroyed -- this would not have been the case with a direct current glow. Such evidence indicates that the effect of sputtering has been considerably reduced.

Observation of the voltage wave shape (Fig. 23a), from one side of the glow to the coil centertap, revealed that there were no high voltage peaks such as were observed with the low frequency glow. This is due to the fact that at these high frequencies the conductivity of the glow gap does not drop to zero when the voltage across the glow passes through zero, because the air in the gap does not completely deionize (Ref. 12). In order to retain this desirable effect at high velocities, it would, of course, be necessary to decrease the gap spacing (or increase the frequency) in order to prevent the positive ions within the electrode gap from being completely blown out in the time which it takes to reverse the polarity of the glow.

Introduction of turbulence into the air stream (about 15 m/sec.) indicated that the 100 KC wave was modulated as shown in Fig. 23b. The percent modulation was about 2%, indicating that some variation of standard radio practice should be used to separate the turbulence frequencies from the 100 KC signal.

Having observed that the 100 KC glow has the above mentioned desirable characteristics, it was decided to investigate such a glow quantitatively. To this end the circuit shown in Fig. 24 is being constructed. This circuit will make it possible to operate the 100 KC glow at either constant peak current or voltage. It will also be possible to measure the current and voltage across the glow without destabilizing the glow. A rectifying circuit will be used to separate the turbulence from the glow frequency. At the time of writing no experimental work has been done with this circuit.

6.00 CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

6.01 The Direct Current Glow

A glow discharge can be maintained and is stable in a transverse air stream at pressures near atmospheric throughout the subsonic velocity range and at supersonic velocities up to a Mach number of 1.5. There are no indications that this Mach number represents the upper limit of the velocities at which stable operation is possible. With current held constant, the direct current voltage across the glow discharge responds quantitatively to velocity changes with a sensitivity depending chiefly upon the spacing between the electrodes.

It has been indicated that sputtering of the electrodes is the chief cause for the scatter of the data and prevents exact reproduction of the calibration curves.

In future work it would be desirable to study the effect of electrode shape and configuration on sputtering and the sensitivity of the direct current glow. In this connection a further study of asymmetric electrode shapes, initiated by Mettler to offset the effect of asymmetric electrode burning, might be useful.

6.02 Low Frequency Alternating Glow

It has been shown that a low frequency alternating glow can be maintained and is sensitive to turbulent fluctuations in a transverse air stream.

Further research should be directed towards the development of circuits with a faster switching action to eliminate the high voltage peak at the beginning of each cycle. In order to eliminate interference with the turbulence frequencies, low frequency switching devices (say, 15 seconds per cycle) are needed. Measuring circuits which do not destabilize the glow also need to be developed. A device of this general nature appears to be entirely feasible.

6.03 High Frequency Alternating Glow

It has been shown that the 100 KC glow qualitatively satisfies most of the requirements of a turbulence measuring instrument and that the effect of sputtering has been, to a large extent, eliminated.

Since this instrument also seems to be promising, future work will be directed towards the completion of the circuit shown in Fig. 24. Quantitative data such as calibration curves, effect of electrode shape and spacing will be obtained. It would also be desirable to investigate the effect of velocity and electrode spacing on the frequency at which the glow operates without the high voltage peaks (Section 5.00). To measure turbulence at supersonic speeds the frequency of the glow will probably have to be increased to something like 200 KC.

The frequency response of the direct current, low frequency and high frequency alternating glows must be investigated before a final evaluation of the turbulence measuring capabilities of these instruments can be made. In any case both the low frequency (< 100 cy/sec.) and the very high frequency (> 100 KC) glows show sufficient promise to warrant their further development.

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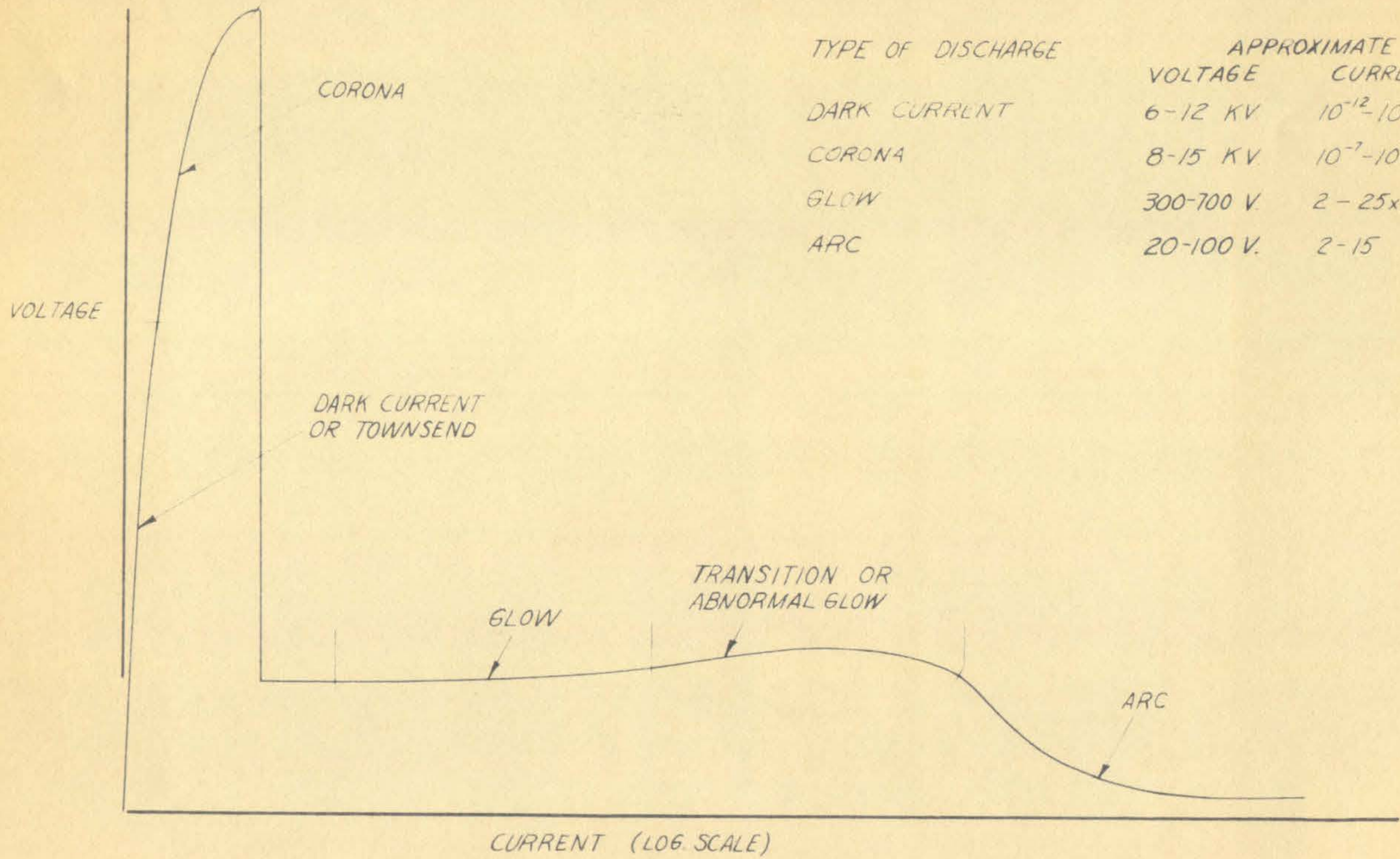


TYPE OF DISCHARGE	APPROXIMATE VOLTAGE	APPROXIMATE CURRENT
DARK CURRENT	6-12 KV	10^{-12}-10^{-9} A
CORONA	8-15 KV	10^{-7}-10^{-6} A
GLOW	300-700 V	$2-25\times10^{-3}$ A
ARC	20-100 V.	2-15 A

VOLTAGE VS CURRENT FOR DISCHARGE ACROSS AN AIR GAP AT ATMOSPHERIC PRESSURE

PAGE 30
FIG. 1

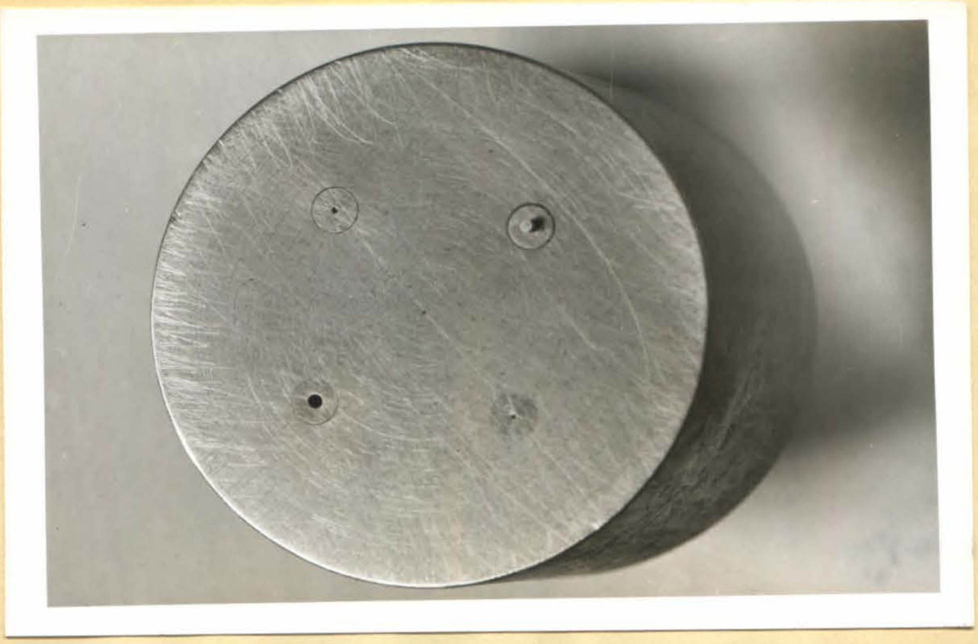


Fig. 2 Flat Electrodes Polishing Jig

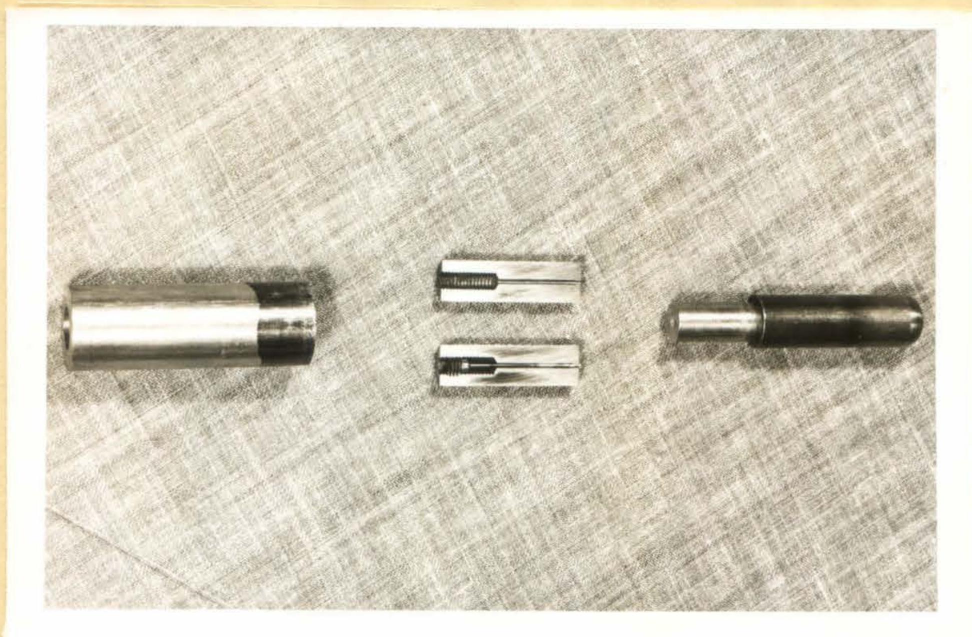
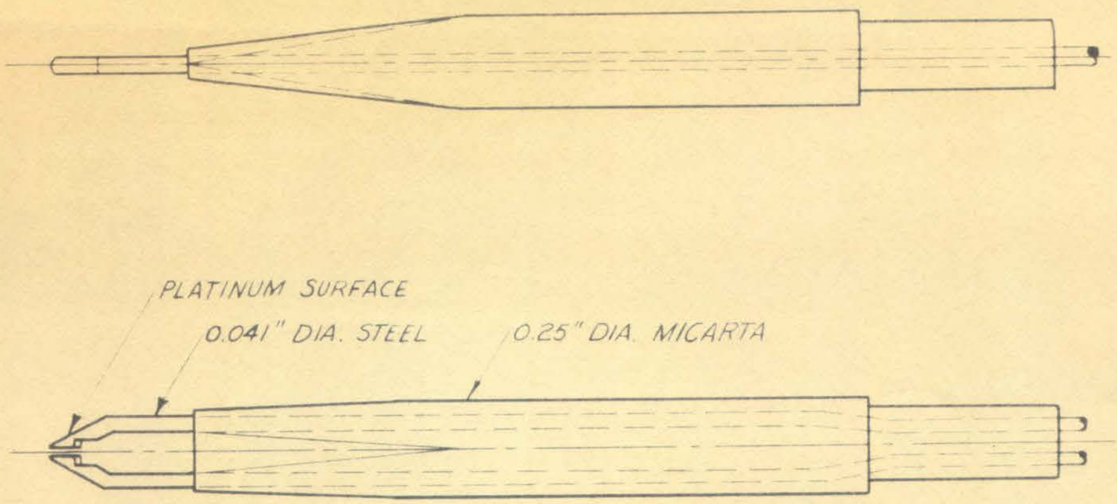
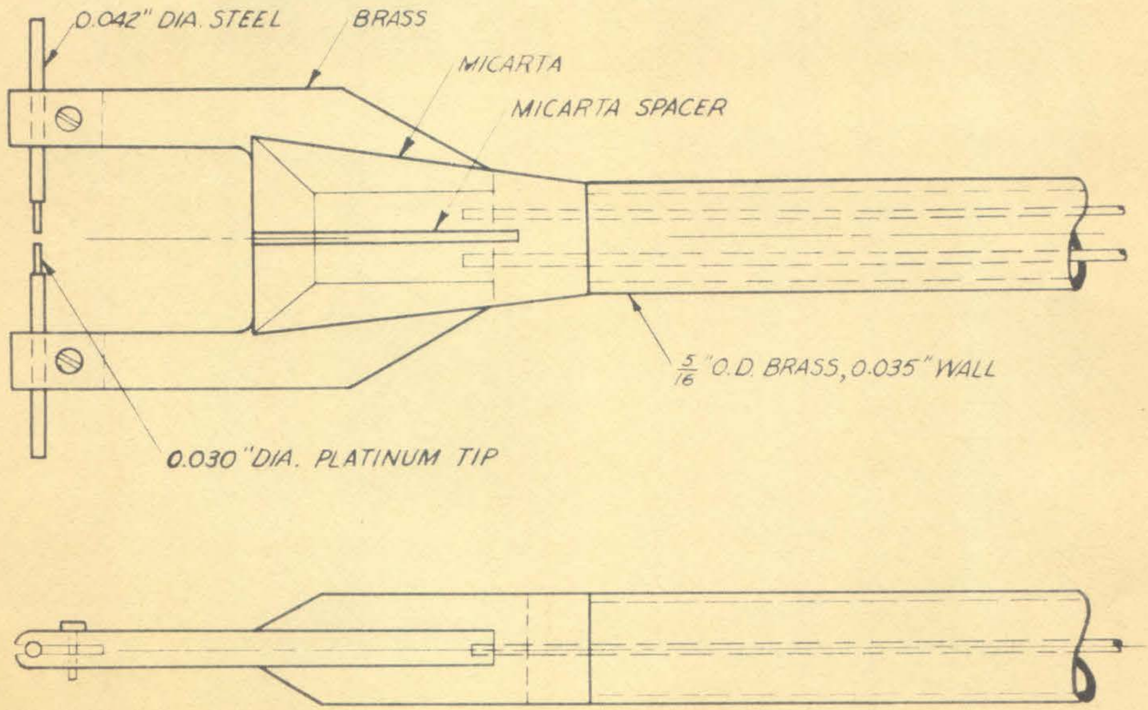


Fig. 3 Spherical Ended Electrodes Cold-Forging Jig



(a) HIGH SPEED PROBE (DOUBLE SIZE)



(b) LOW SPEED PROBE (DOUBLE SIZE)

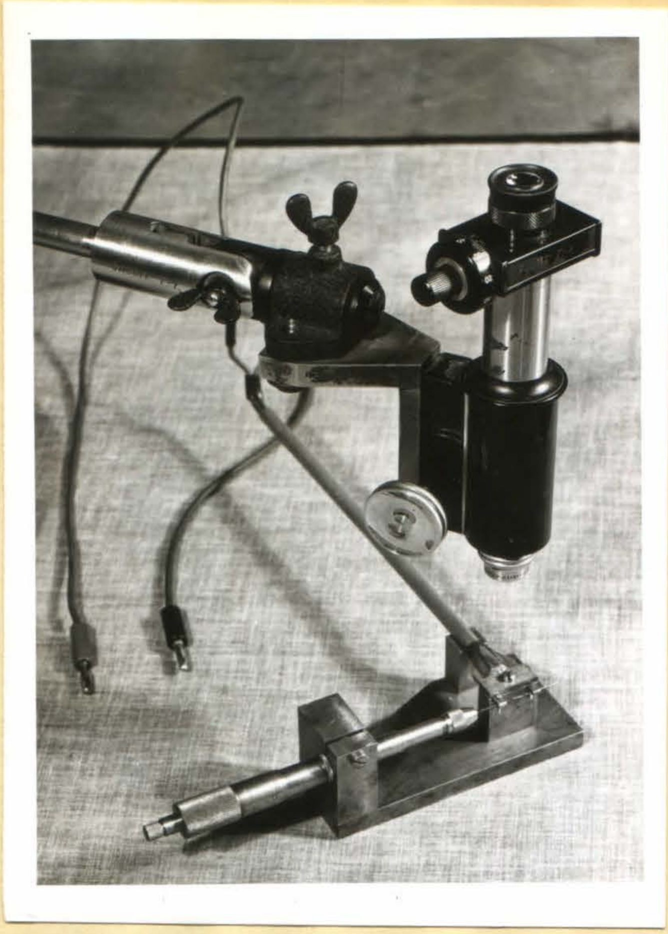


Fig. 5 Spacing Jig, Low Speed Probe and Comparator

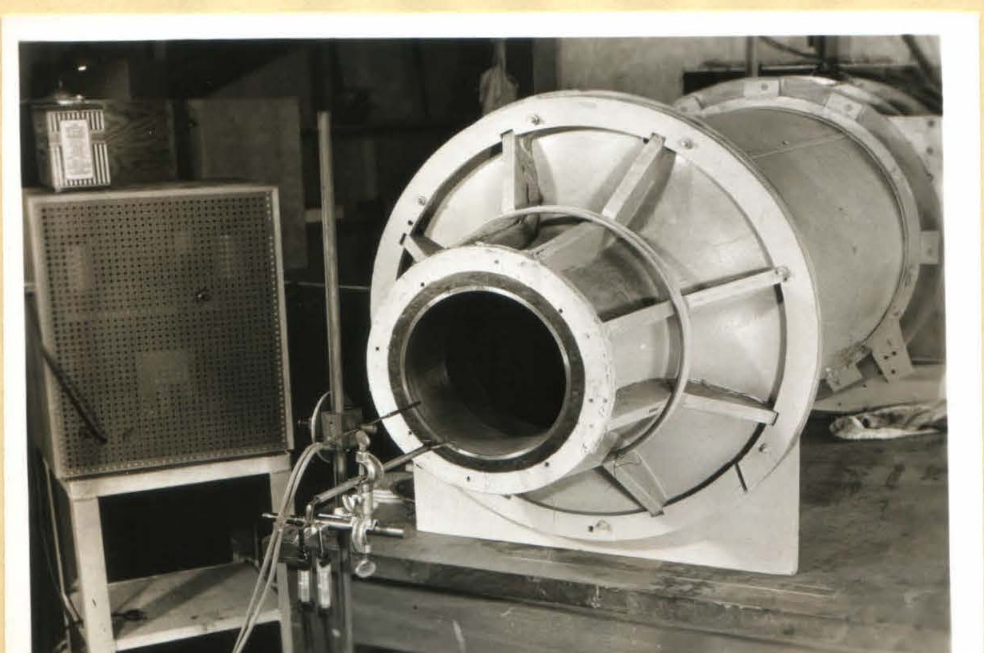
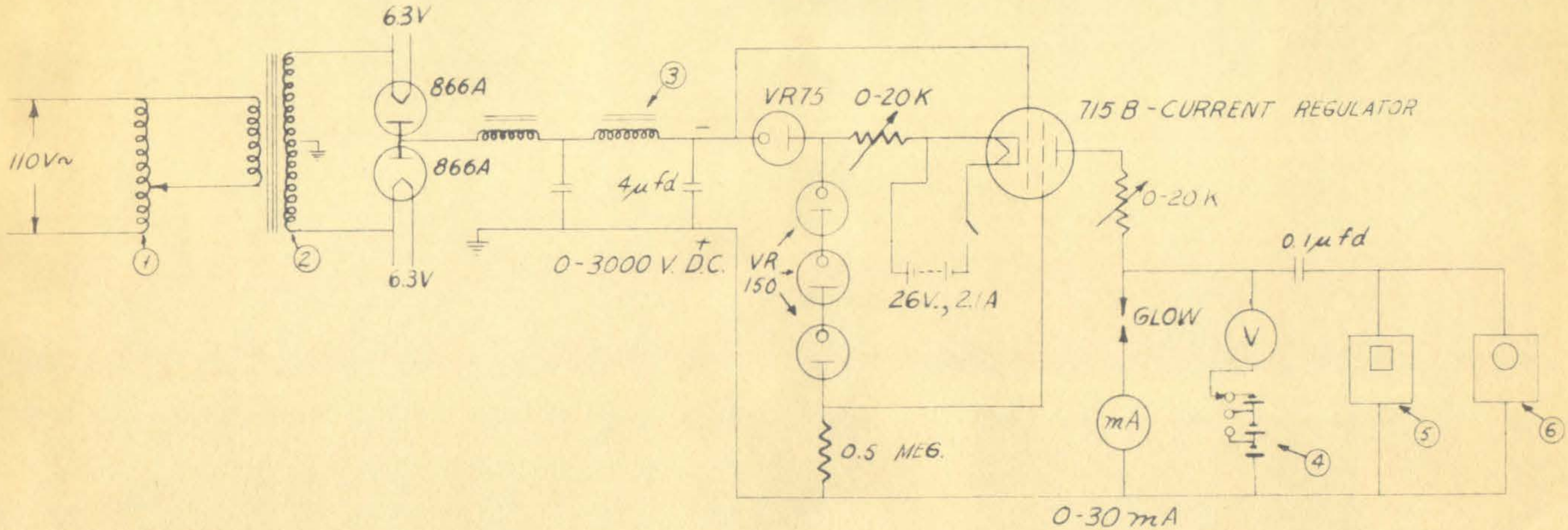


Fig. 6 Low Speed Probe Mounting and 8" Jet

CIRCUIT ELEMENTS

1. POWERSTAT
2. NEON TRANSFORMER (G.E. 51G5)
3. SWINGING CHOKES (THORDARSON T-20C50)
4. BUCKING BATTERIES - 45 VOLT STEPS
5. A.C. VACUUM TUBE VOLTMETER
6. CATHODE RAY OSCILLOSCOPE



D.C. GLOW ANEMOMETER CIRCUIT

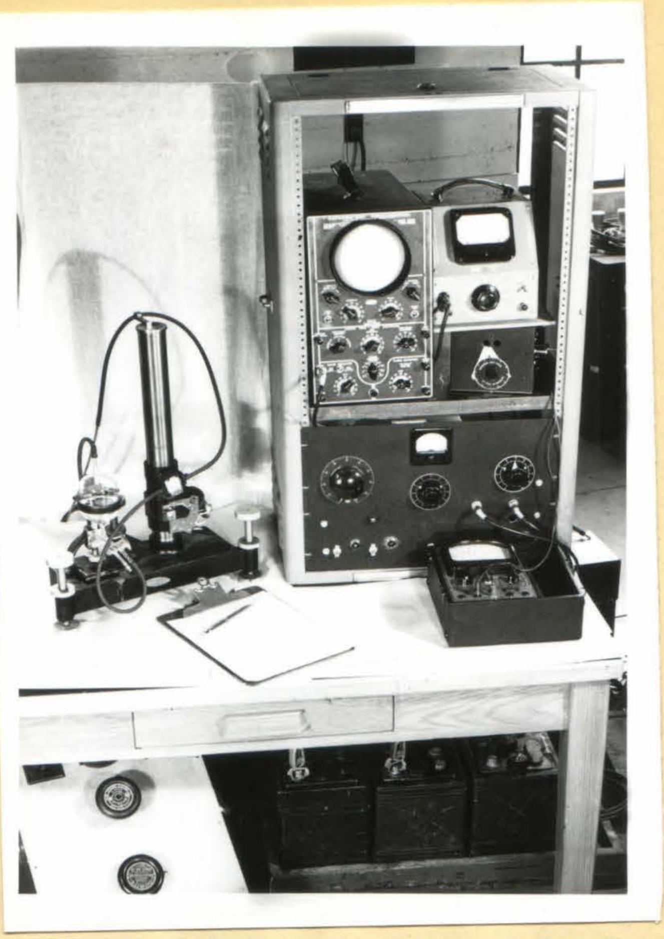
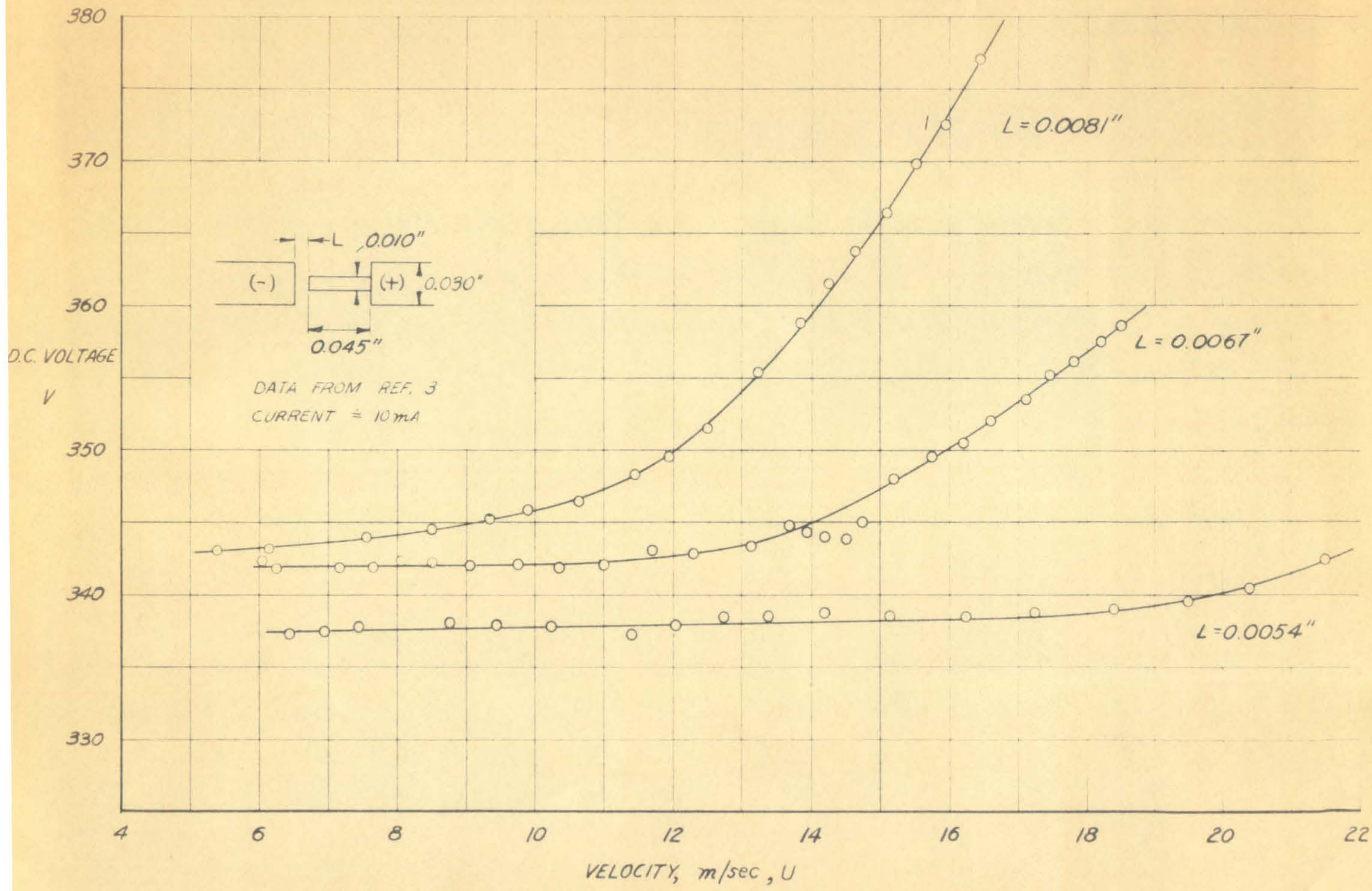
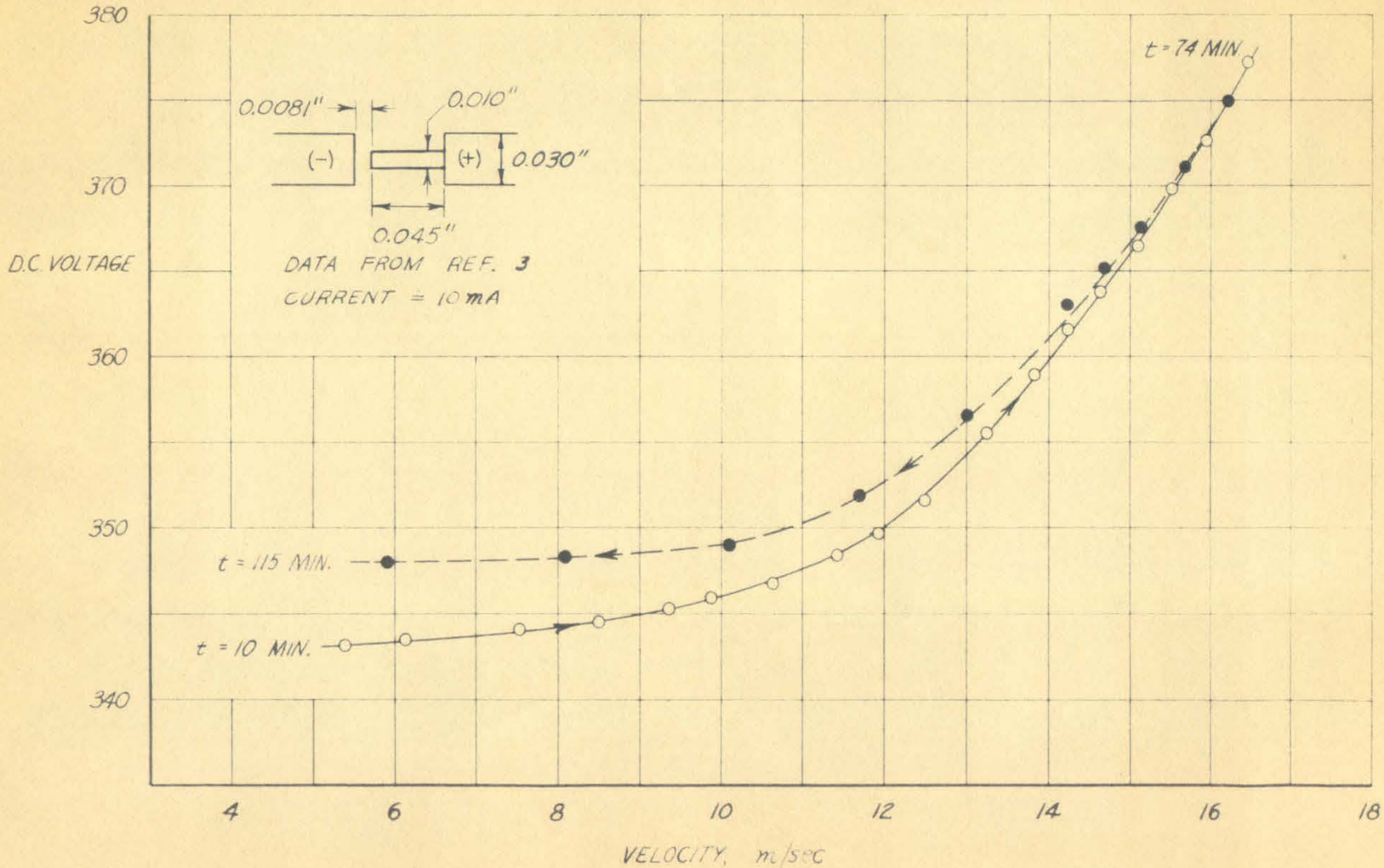


Fig. 8 D.C. Glow Experimental Set-Up

Fig. 9 D.C. Power Supply and Current Regulator



VOLTAGE - VELOCITY CALIBRATION CURVES

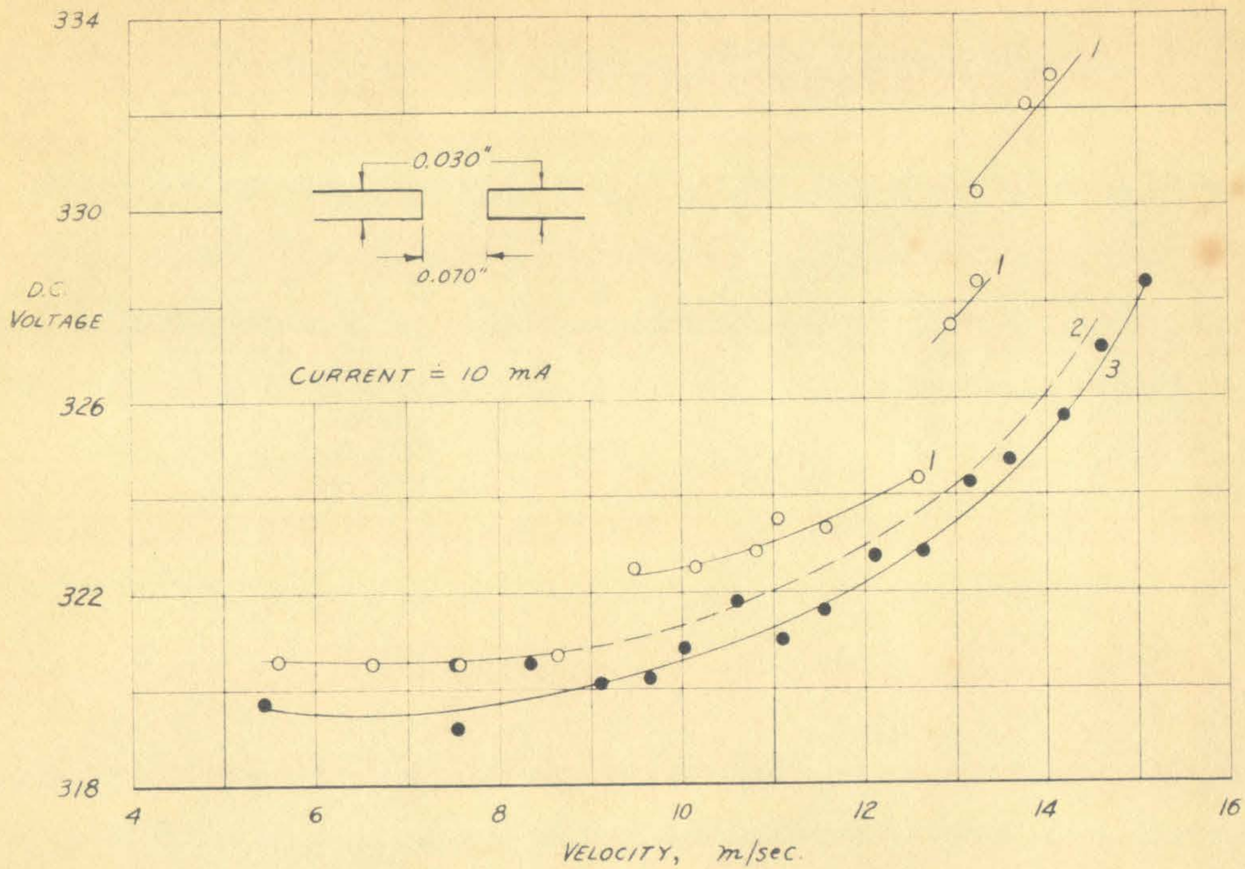


EFFECT OF SPUTTERING

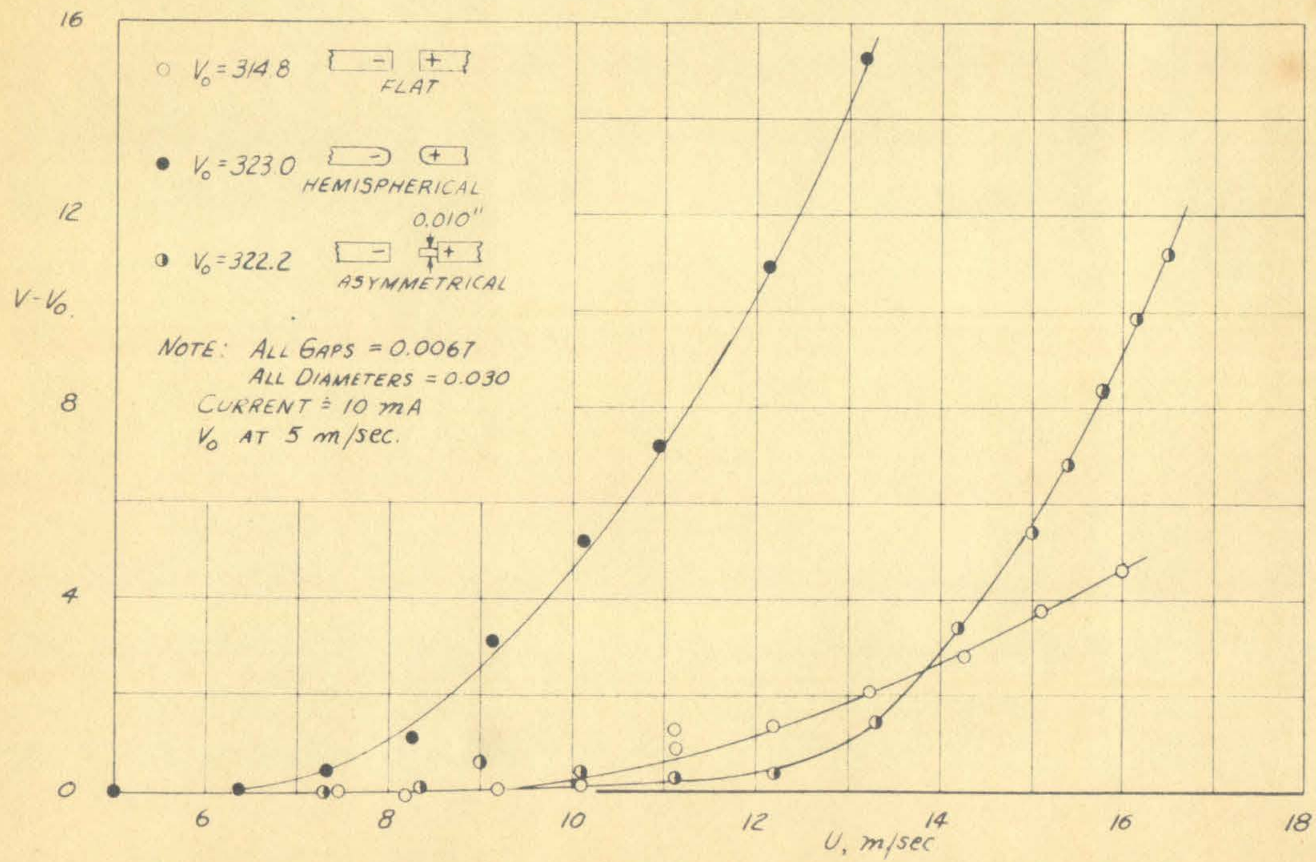
(a) Cathode

(b) Anode

Effect of Sputtering on Electrodes (0.030 Inches Diameter)
After 1.5 Hours of Operation at 10 mA and Electrode Spacing of 0.070 Inches
(Direction of Air Stream is from Left to Right)



EFFECT OF INSTABILITIES ON VOLTAGE - VELOCITY CALIBRATION CURVE



EFFECT OF ELECTRODE SHAPE

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FIG. 14

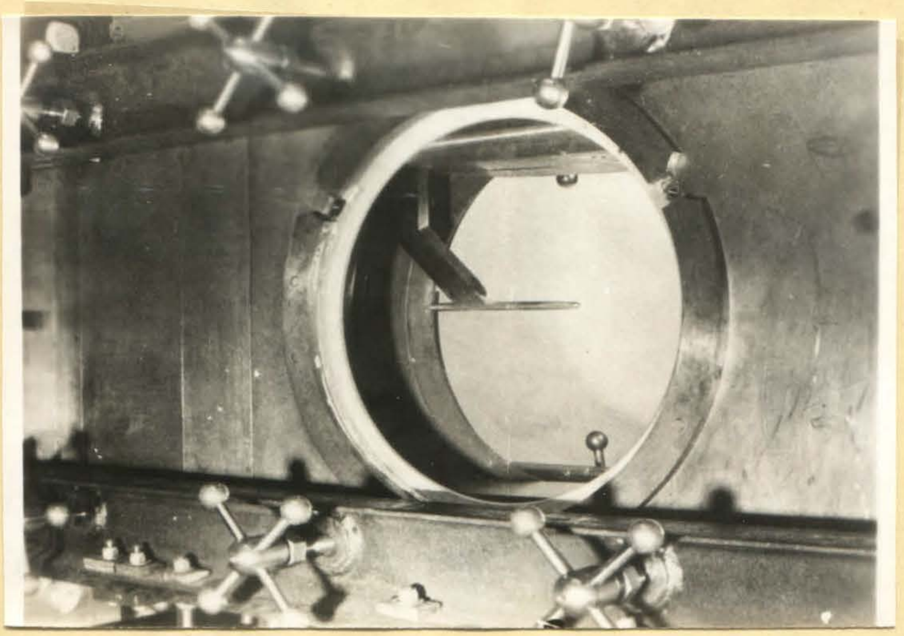


Fig. 15 Supersonic Probe in GALCIT 4" x 10"
Transonic Tunnel

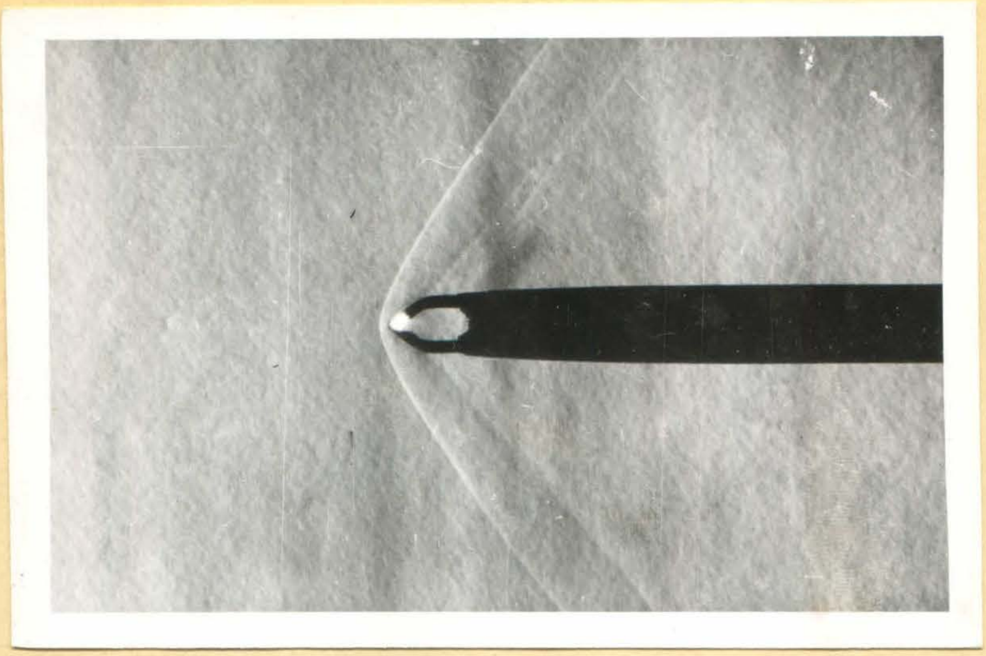


Fig. 16 Schlieren Photograph of Probe at M = 1.2 with Glow On

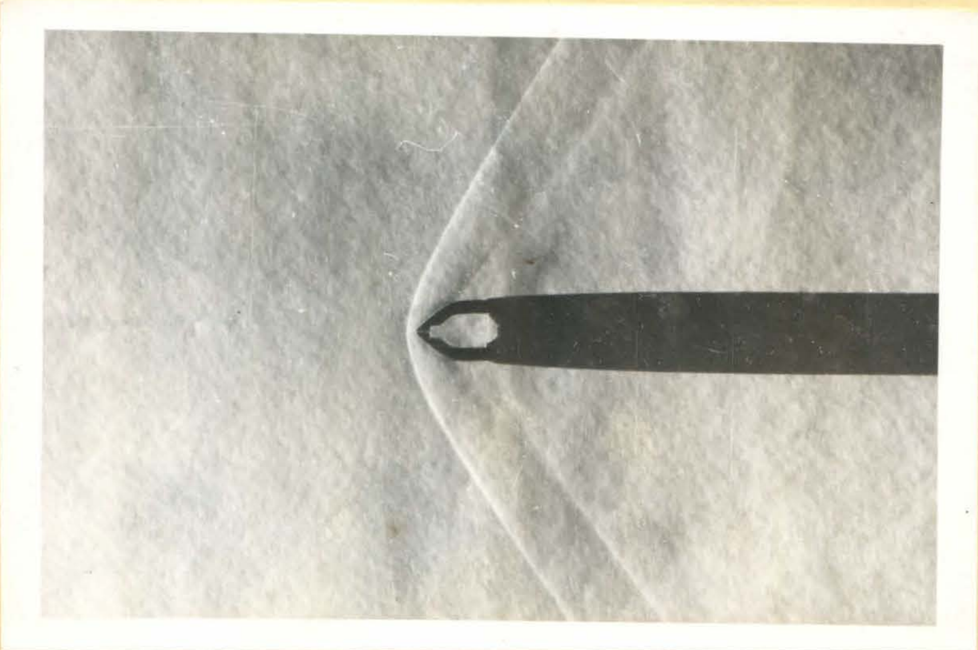
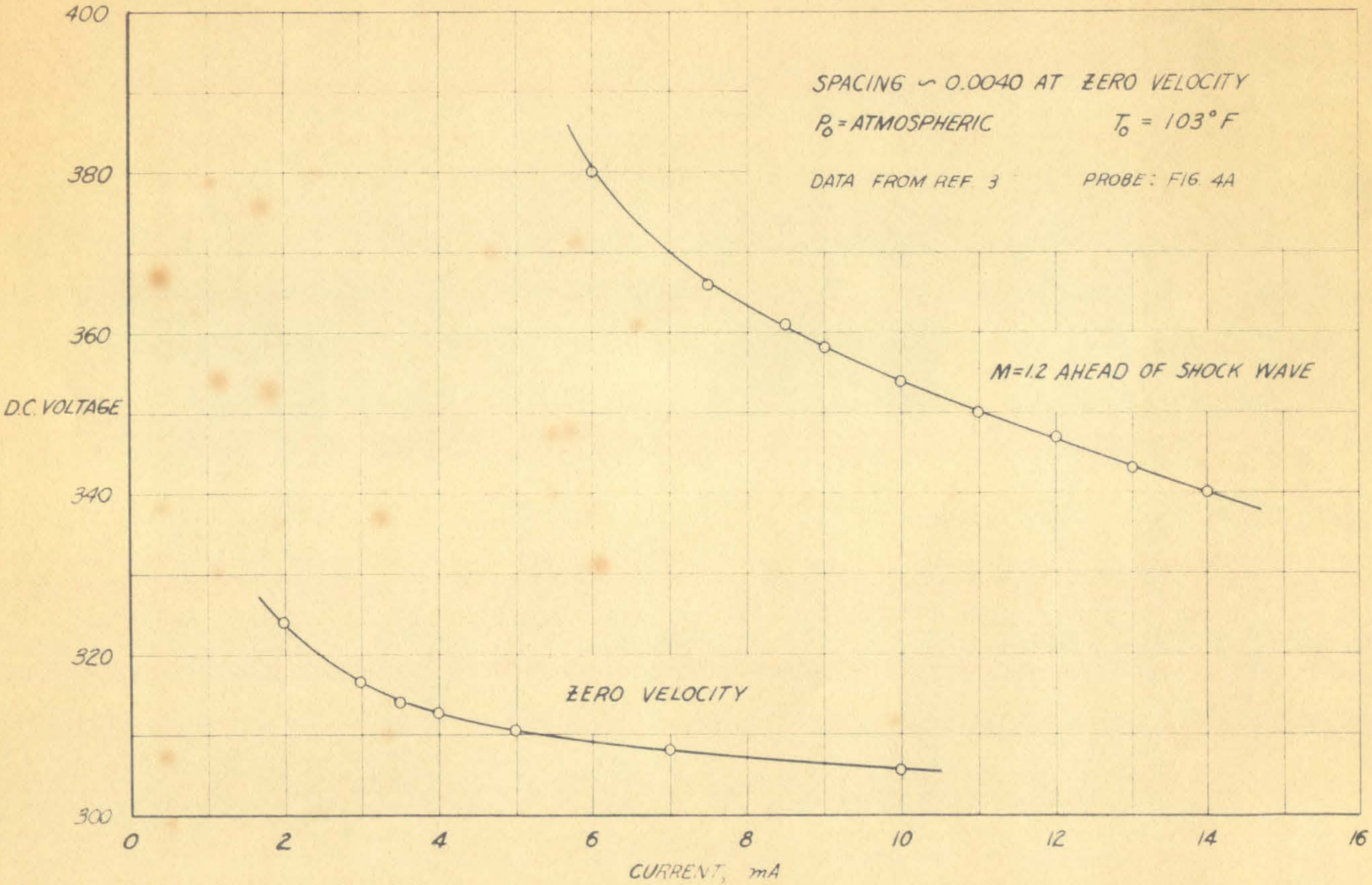
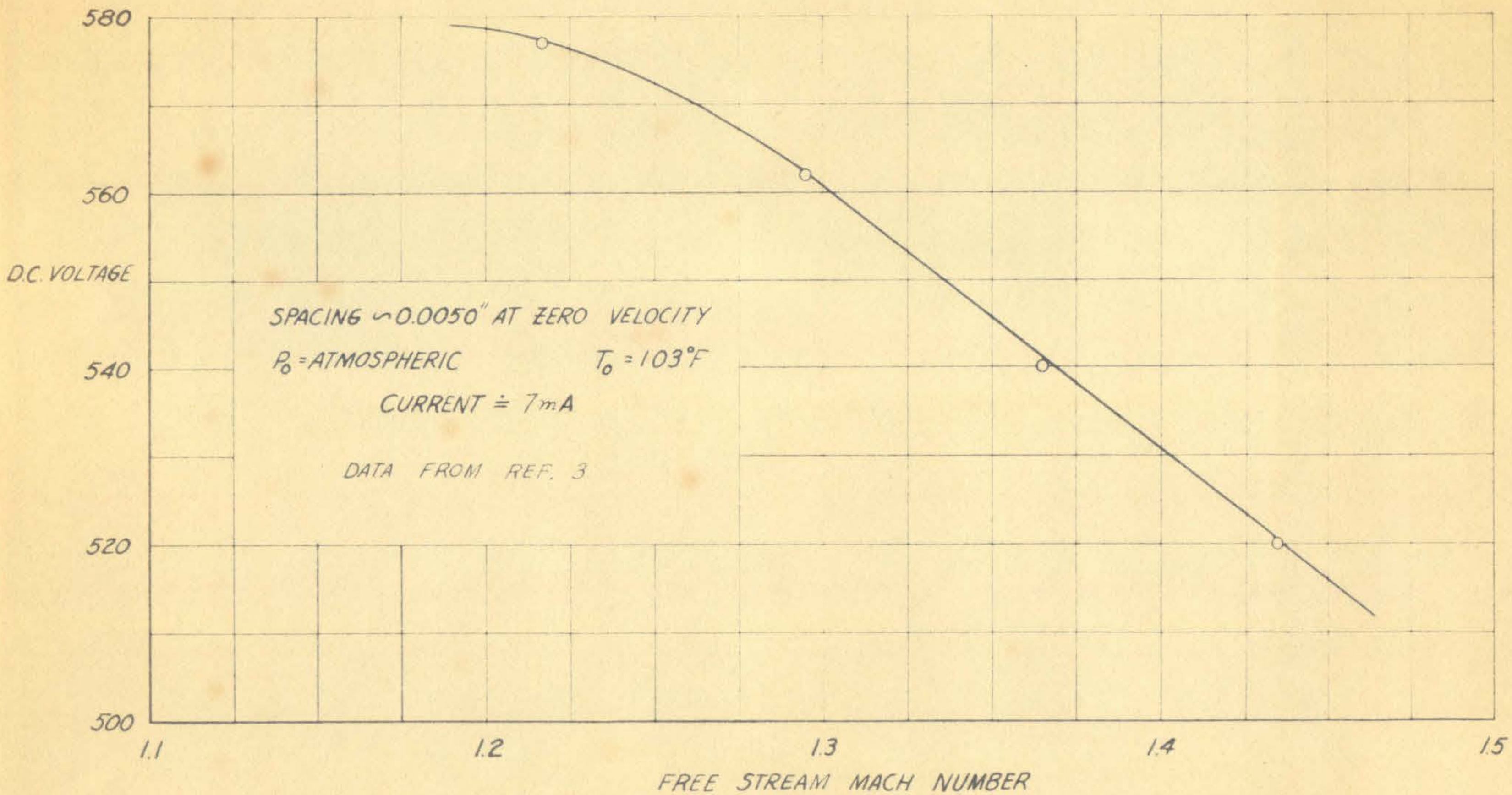


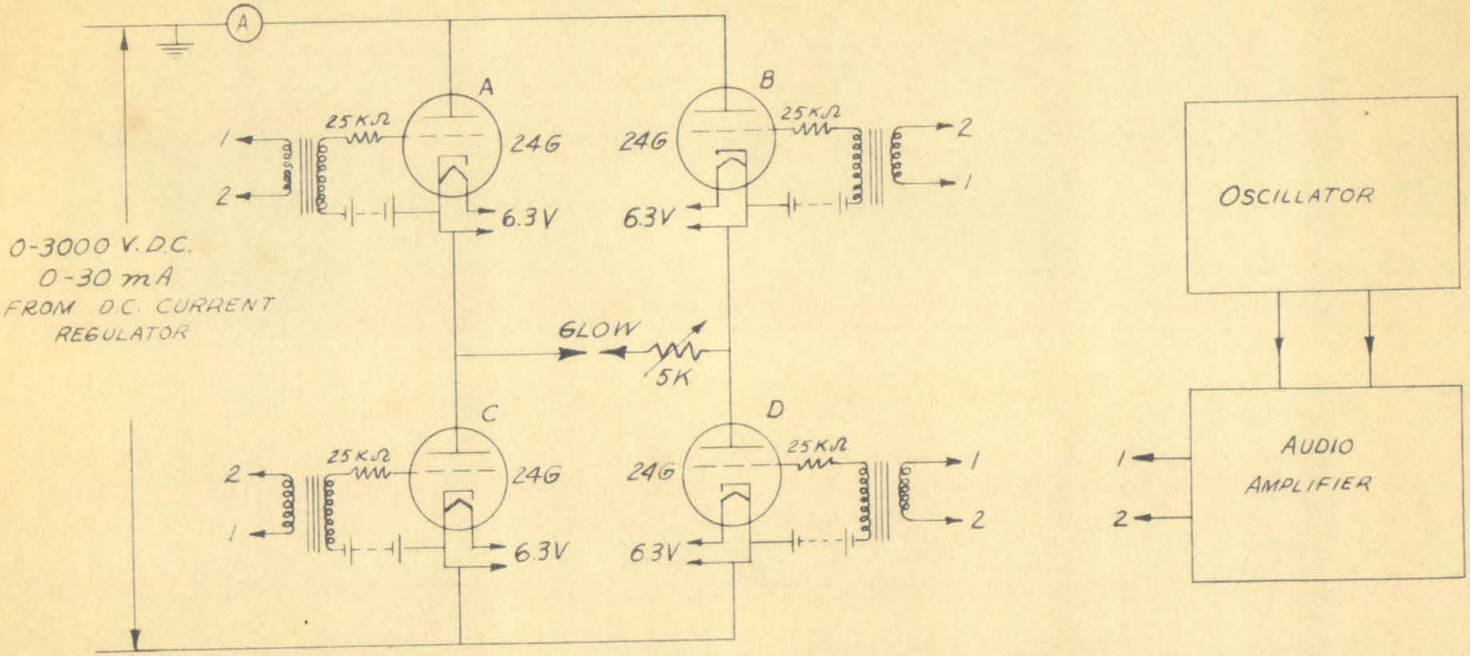
Fig. 17 Schlieren Photograph of Probe at M = 1.2 without Glow



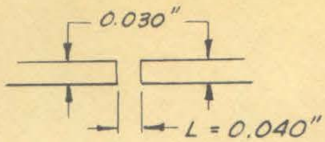
CURRENT - VOLTAGE CURVES

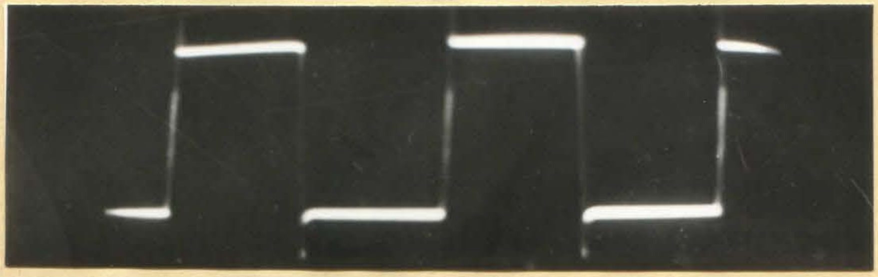


VOLTAGE - MACH NUMBER RELATION



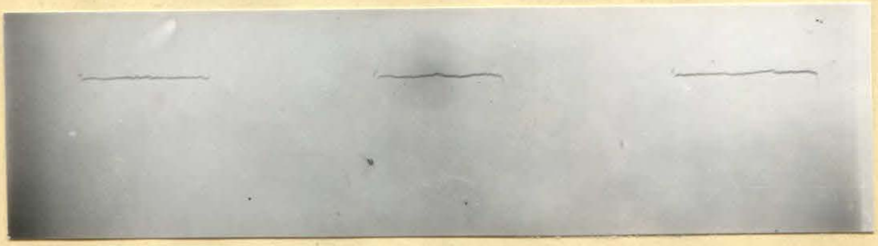
A.C. GLOW SWITCHING CIRCUIT 7-2000 CYCLES





(a) With No Turbulence

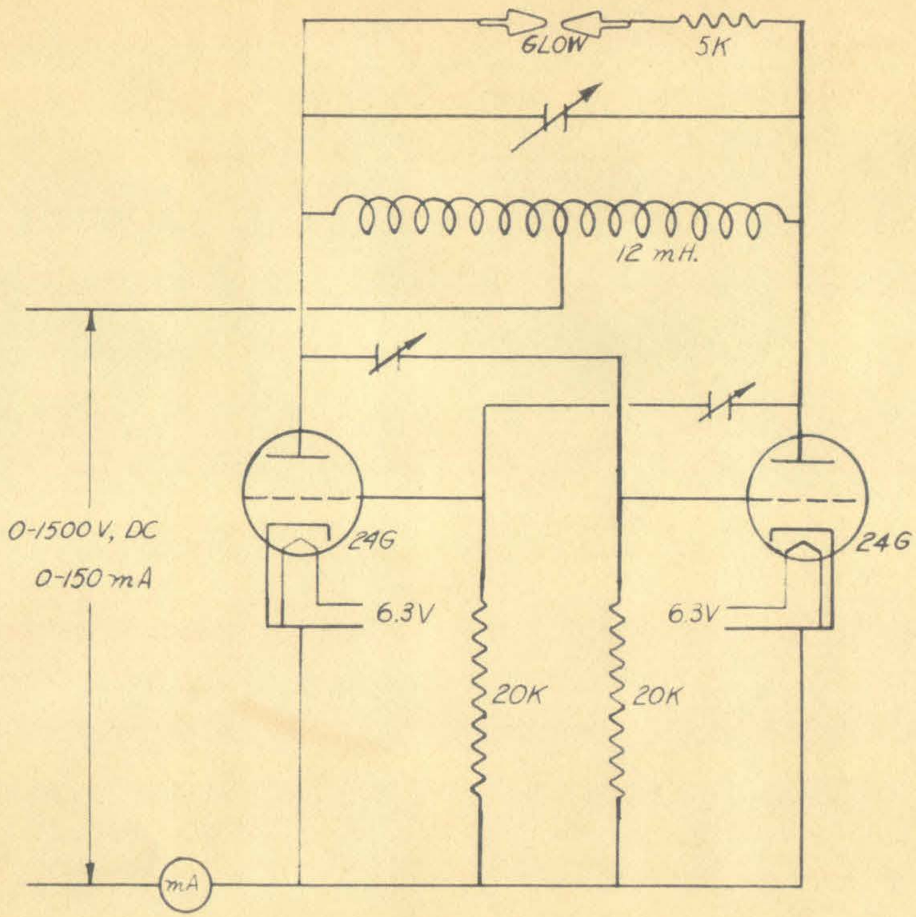
(Note Starting Pulse at Beginning of Each Square Wave)
Switching Frequency = 200 cy/sec
Current = 15 mA



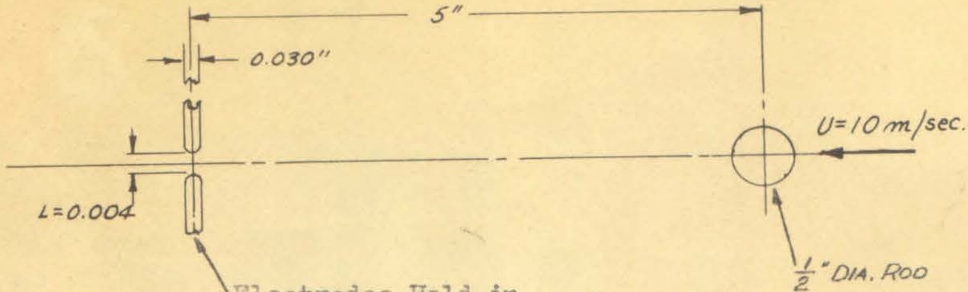
(b) With Turbulence

Turbulence Produced by Air-Jet from Compressed Air Supply
Top of Square Wave is Shown
Switching Frequency = 60 cy/sec
Current = 20 mA

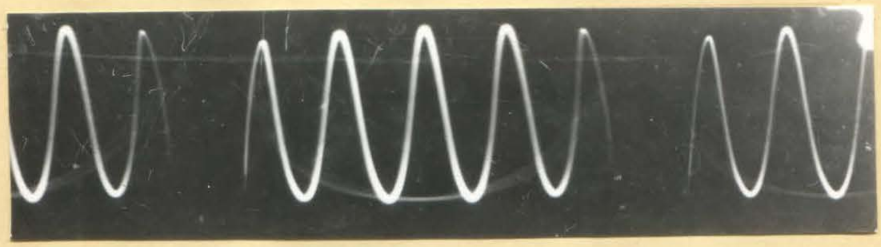
Glow Voltage Wave Shape from Low
Frequency Switching Circuit



PUSH-PULL NEGATIVE RESISTANCE OSCILLATOR



Electrodes Held in
Probe Shown in Fig. 4b

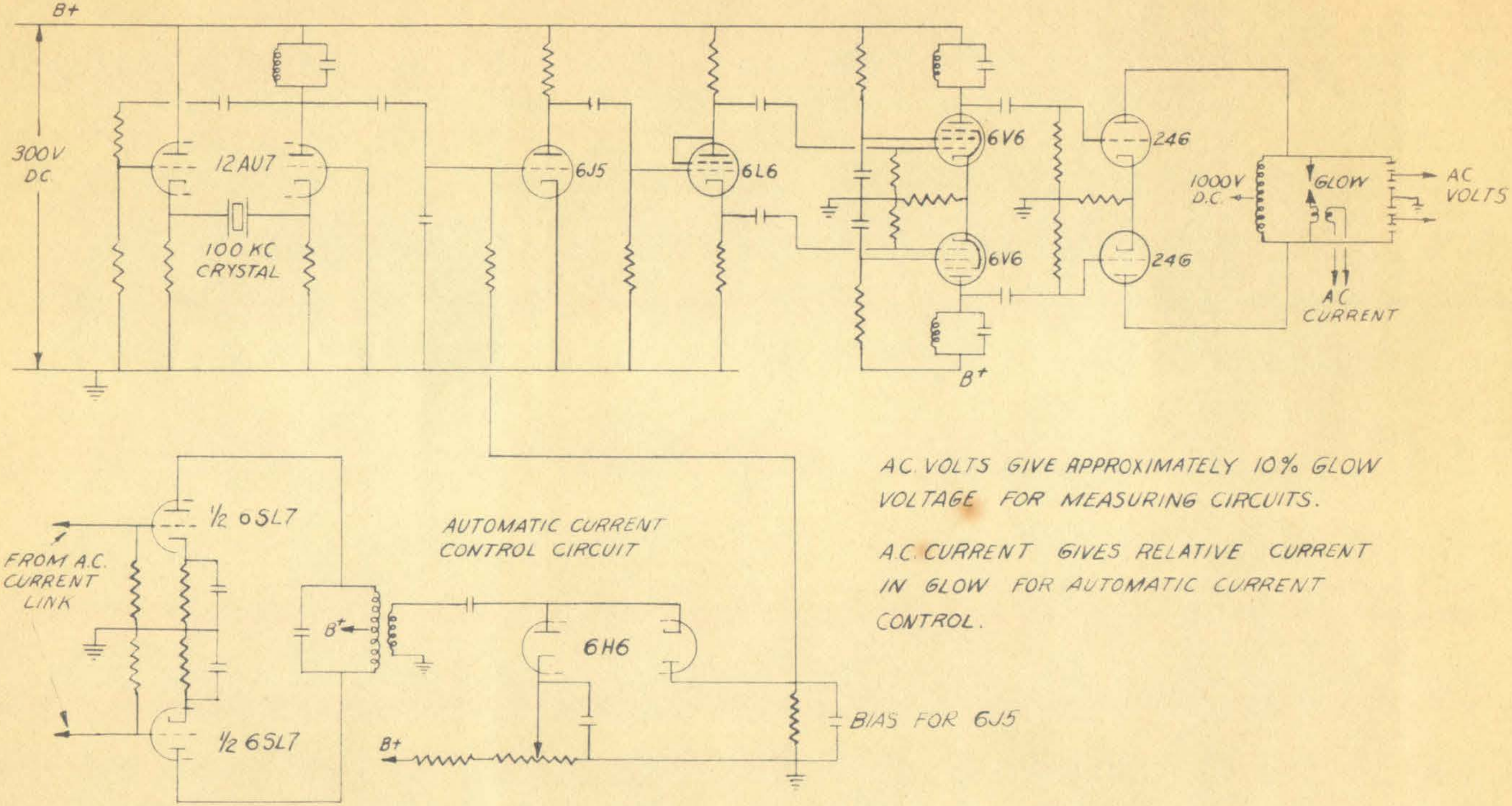


(a) With No Turbulence

(b) With Turbulence

Turbulence Produced as Shown in Above Sketch
The Photograph shows the Modulation, Due to
Turbulence, of the Wave Form Shown Above

Glow Voltage Wave Shape From the 100 KC
Negative Resistence Push-Pull Oscillator



AC VOLTS GIVE APPROXIMATELY 10% GLOW VOLTAGE FOR MEASURING CIRCUITS.

AC CURRENT GIVES RELATIVE CURRENT IN GLOW FOR AUTOMATIC CURRENT CONTROL.

FIG. 24